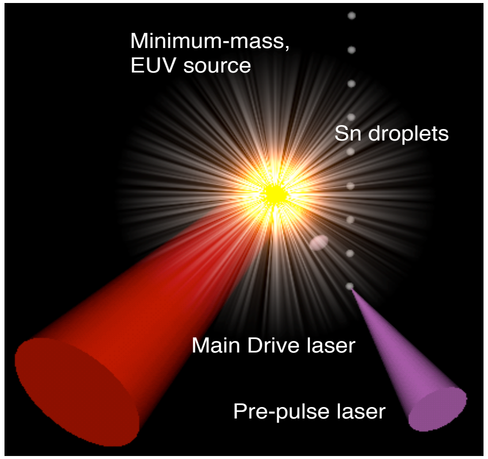
Measurement of CO_2 laser absorption by thin plasma as a 13.5 nm EUV light source

H. Nishimura[1], H. Matsukuma[1], K. Yoshida[1], T. Hosoda[1], A. Yogo[1], N. Tanaka[1], S. Fujioka[1], K. Nishihara[1], A. Sunahara[2], T. Somekawa[2], Y. Takeuchi[2], and T. Yanagida[3]



[1] Institute of Laser Engineering, Osaka University, Japan
[2] Institute for Laser Technology, Japan
[3] Gigaphoton Inc., Japan

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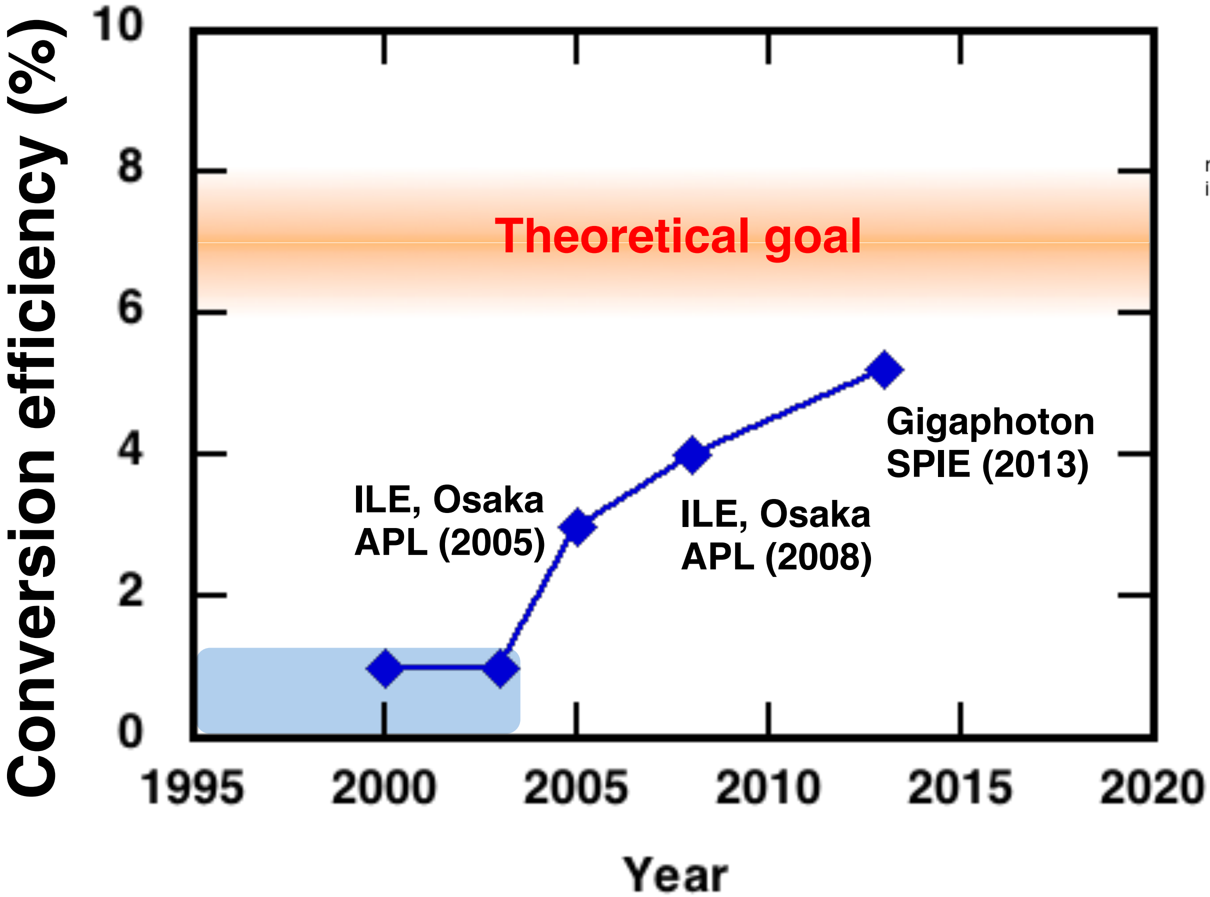
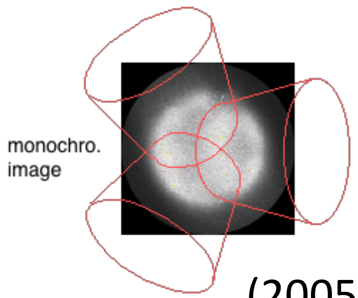
2014 International Workshop on EUV and Soft X-ray Sources, Nov. 3-6, 2014, Dublin, Paper#:S23

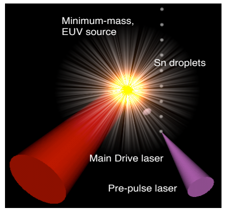
Background

Extensive studies have been made aiming at the theoretical goal of EUV conversion efficiency (CE)





(2005)



(2008)

Use of ps-pulse
(2013)

Y. Shimda, et al., APL 86, 051501 (2005)
S. Fujioka, et al., APL 92, 241502 (2008)
H. Mizoguchi et al., Proc. SPIE 8679, 86790A (2013)

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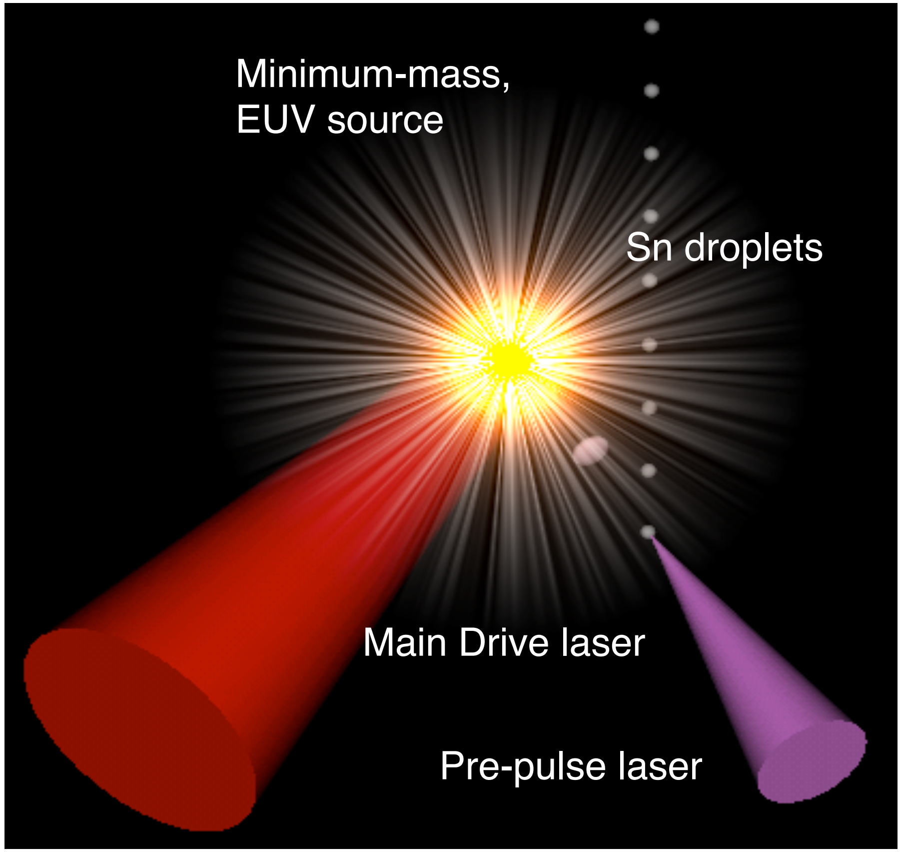
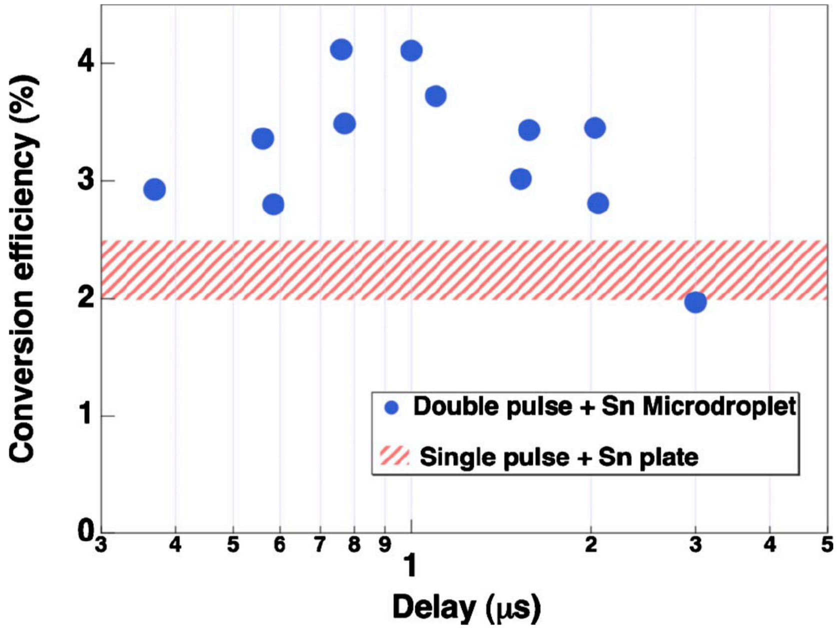
Background

Two-color, double pulse scheme is widely adopted in EUV source for lithography





T_e, n_e, L_{scale}, η_{abs} ?

It is not clarified yet why CE is substantially increased, optimization plasma parameters or increase in laser absorption?

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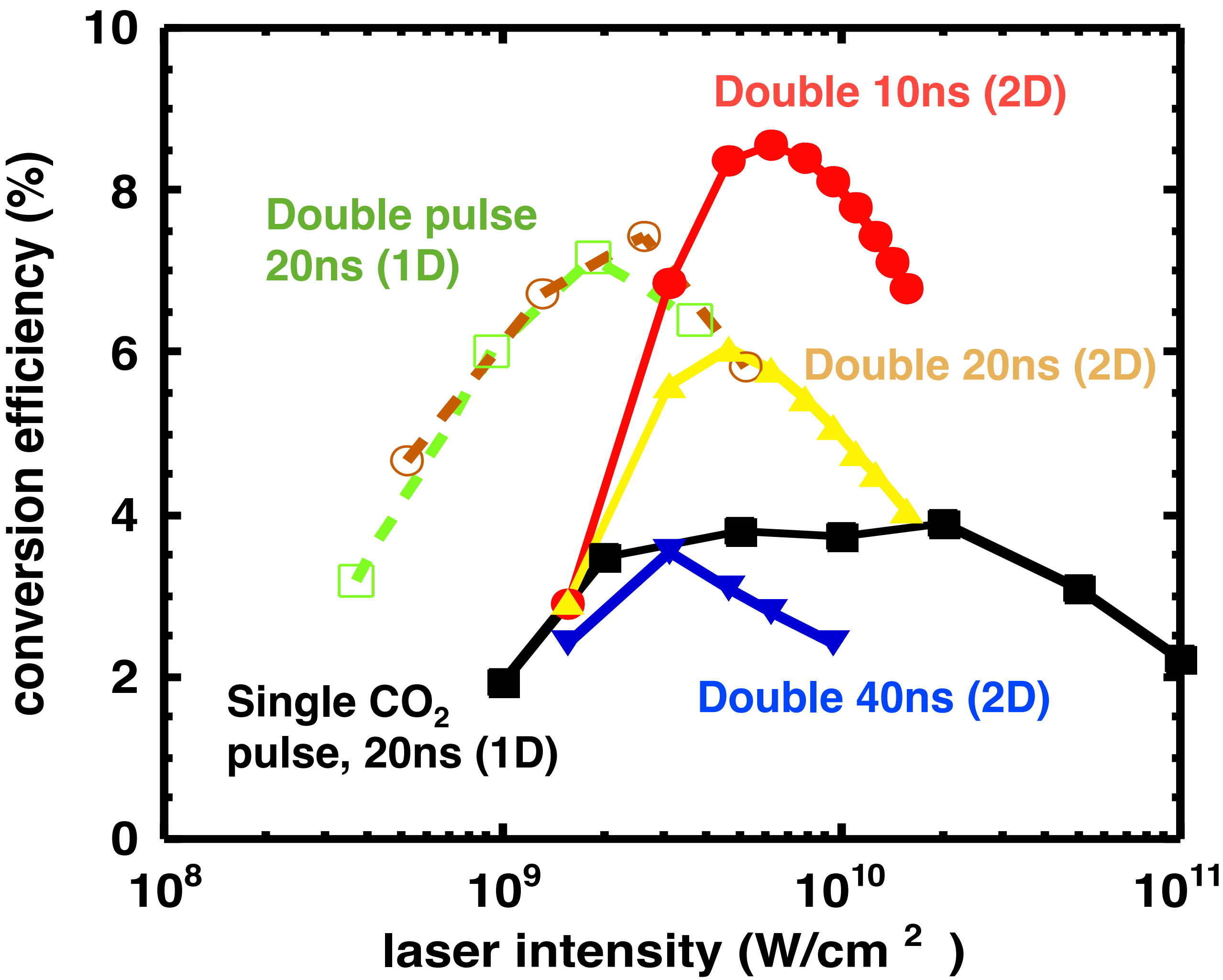
***S.Fujioka *et al.*, APL 92, 241502 (2008).**

Predictions

Double pulse scheme affords 6-8% EUV CEs, twice larger than those given with a single pulse



<Pre-pulse>
$1 \times 10^8 W/cm^2$
10ns (0.53μm)
delay :180ns

In 2D simulation, 150μm pre-formed plasma is initially set. Spot diameter is 800 μm.

HULLAC Opacity
1500 groups in 0-1.5 keV

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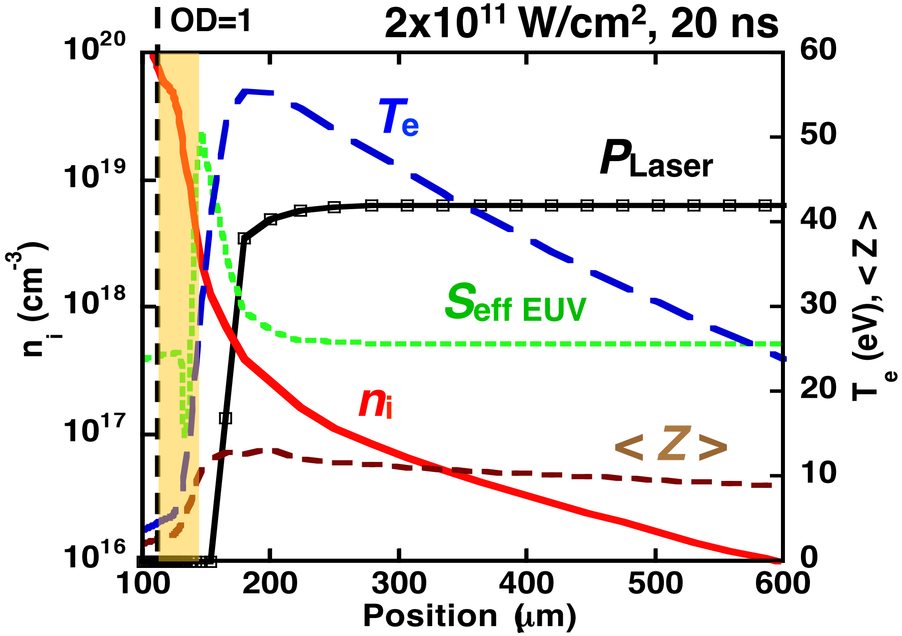
A. Sunahara, OYO BUTSURI 83, 741 (2014)

Predictions

Theoretical predictions infer that increase in EUV CE is resulted from increase in laser absorption

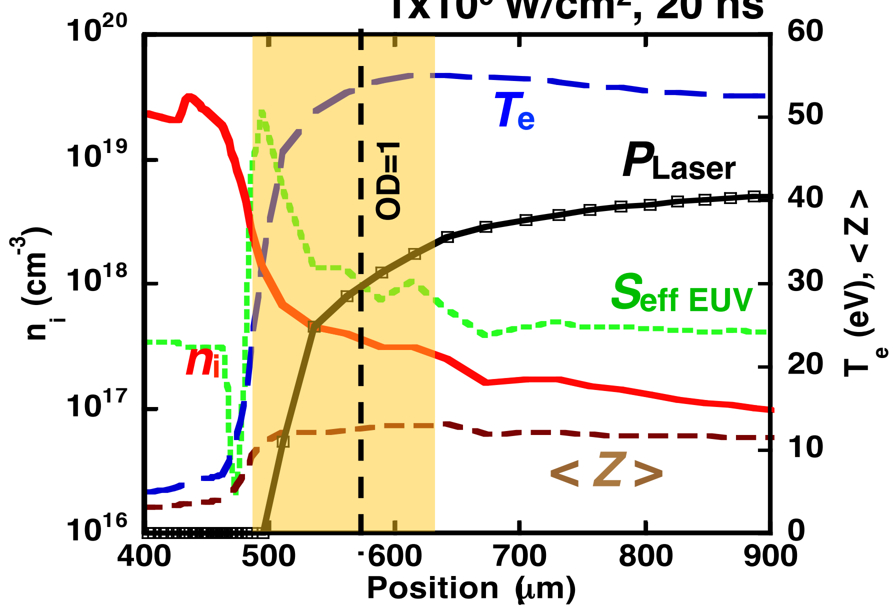
Single pulse

2×10^{11} W/cm^2, 20 ns



Double pulse

1×10^{9} W/cm^2, 20 ns



	Single pulse	Double pulse	
Laser absorption	46%	91%	increase in laser abs.
Radiation CE	48%	69%	increase in rad. CE
$P_{EUV}/P_{x\text{-ray}}$	15%	11%	better spectral purity
EUV CE	3.3%	7.2%	increase in EUV CE

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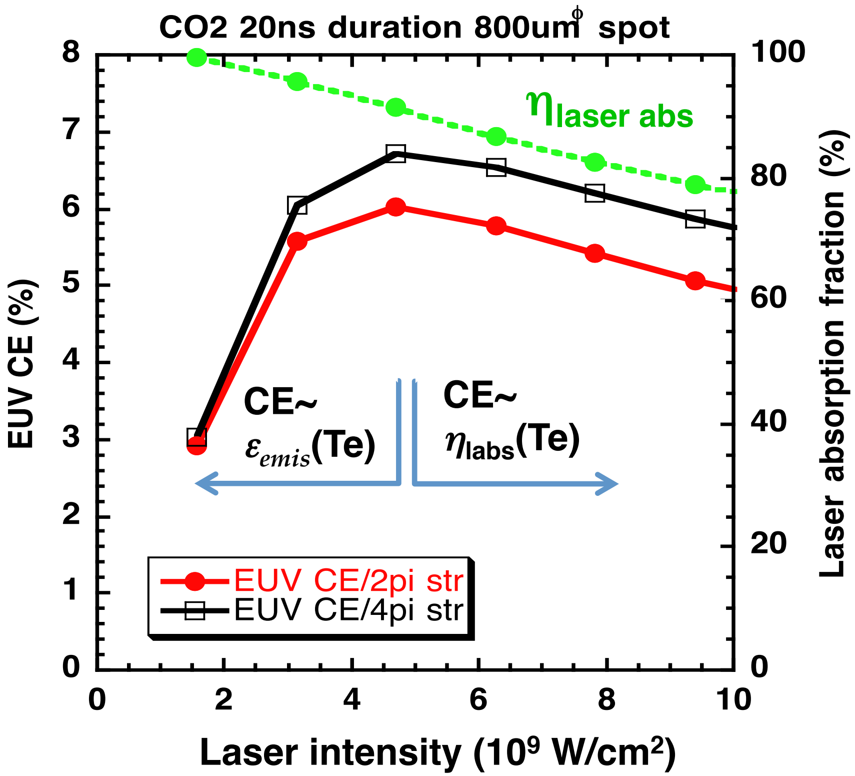
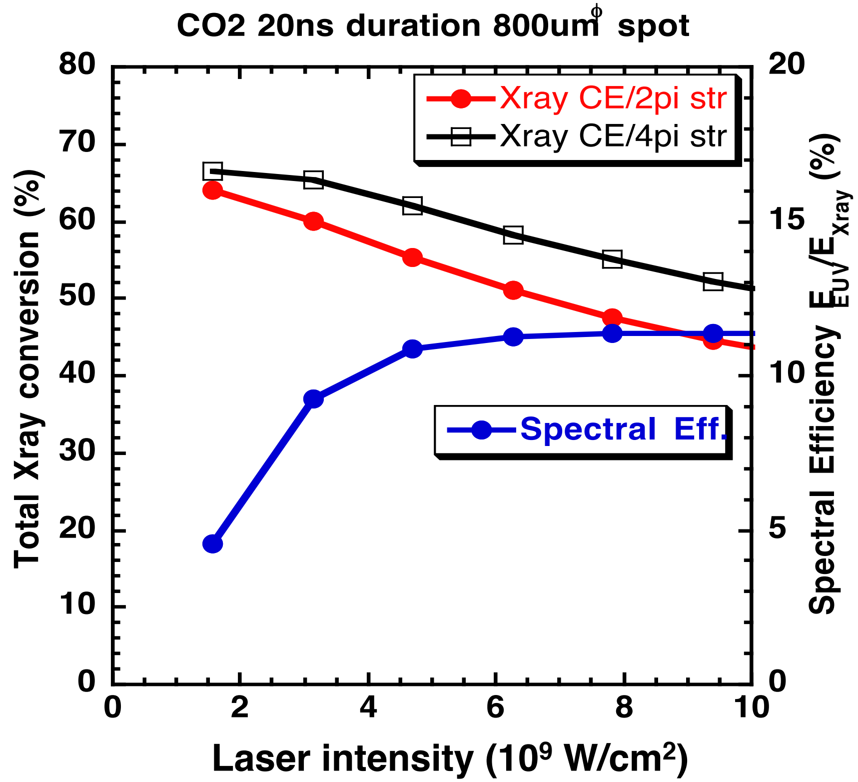
Predictions

With increase in laser intensity, two distinct regions appear for CE, dependent either on T_e or η_{labs}

$$\eta_{laser\ abs.} = 1 - \exp(-\tau L),\ \text{where}\ \tau \propto n_i n_e T_e^{-7/2} Z^2$$





Sn droplet, L=150μm pre-plasma, CO_2 laser beam conversing at the center

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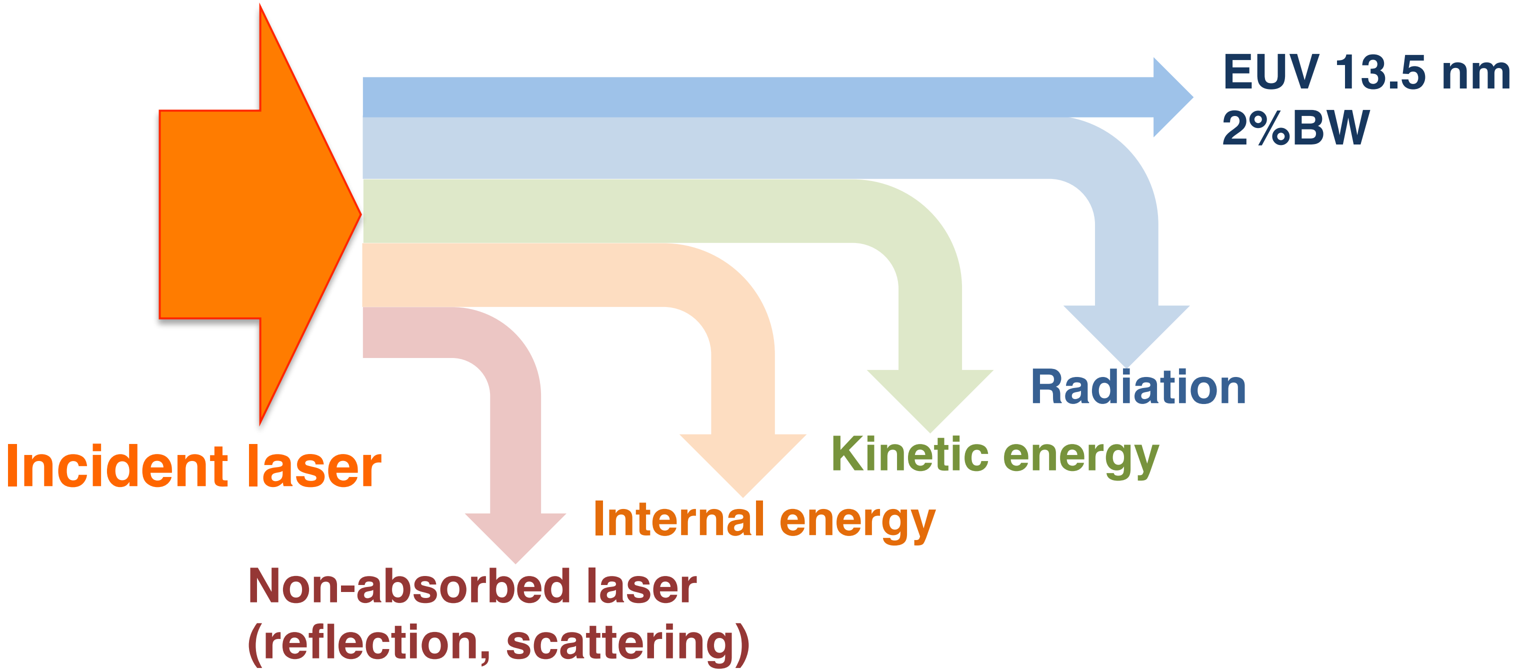
Objectives

1. Experimental verification of CE vs. η_{labs}
2. Optimization for higher η_{labs} hence better CE

$$\eta_{laser\ \text{abs.}} = 1 - \exp(-\tau L),\ \text{where}\ \tau \propto n_i n_e T_e^{-7/2} Z^2$$

Note: excessively long-scale plasma may result in reduction in CE due to "EUV self-absorption"



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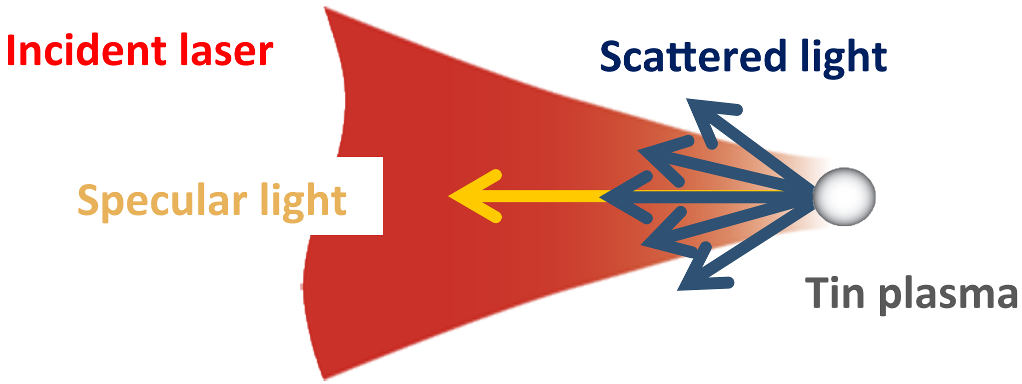
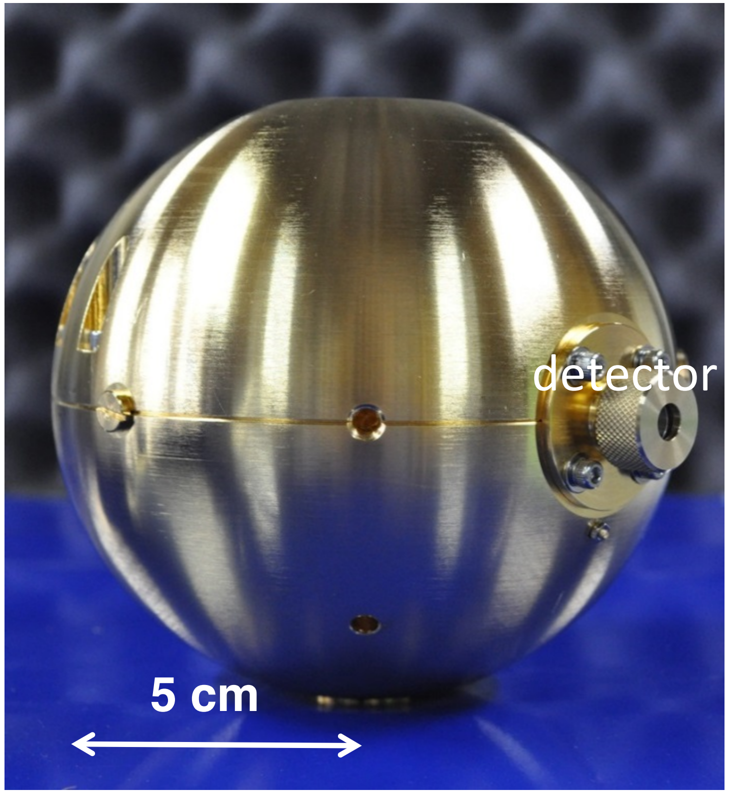
Experiment

We developed an integrating sphere for η_{labs} measurement of CO_2 laser by plasma

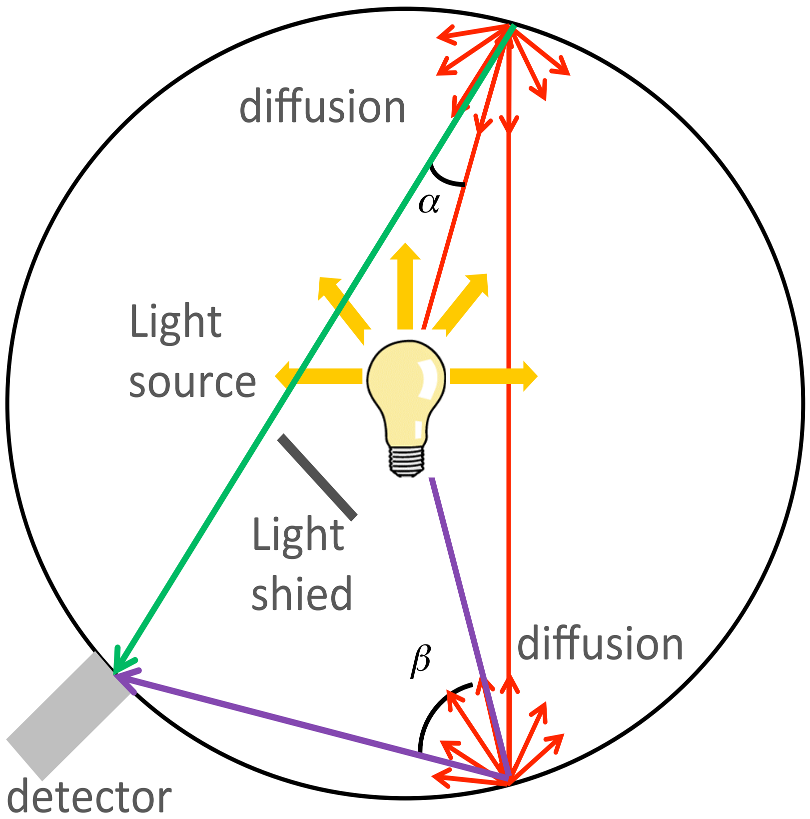


$$\eta_{labs.} = 1 - \frac{I_{specular} + I_{scatter}}{I_{laser}}$$



Experiment

Multi-reflection of scattered light homogenizes its distribution on the inner surface



Light intensity @detector

$$= \frac{\rho\Phi}{S}(1+\rho+\rho^2+\rho^3+\rho^4+\ldots+\rho^{n-1})$$

$$= \frac{\Phi}{S}\frac{\rho}{1-\rho}$$

Φ: light source power

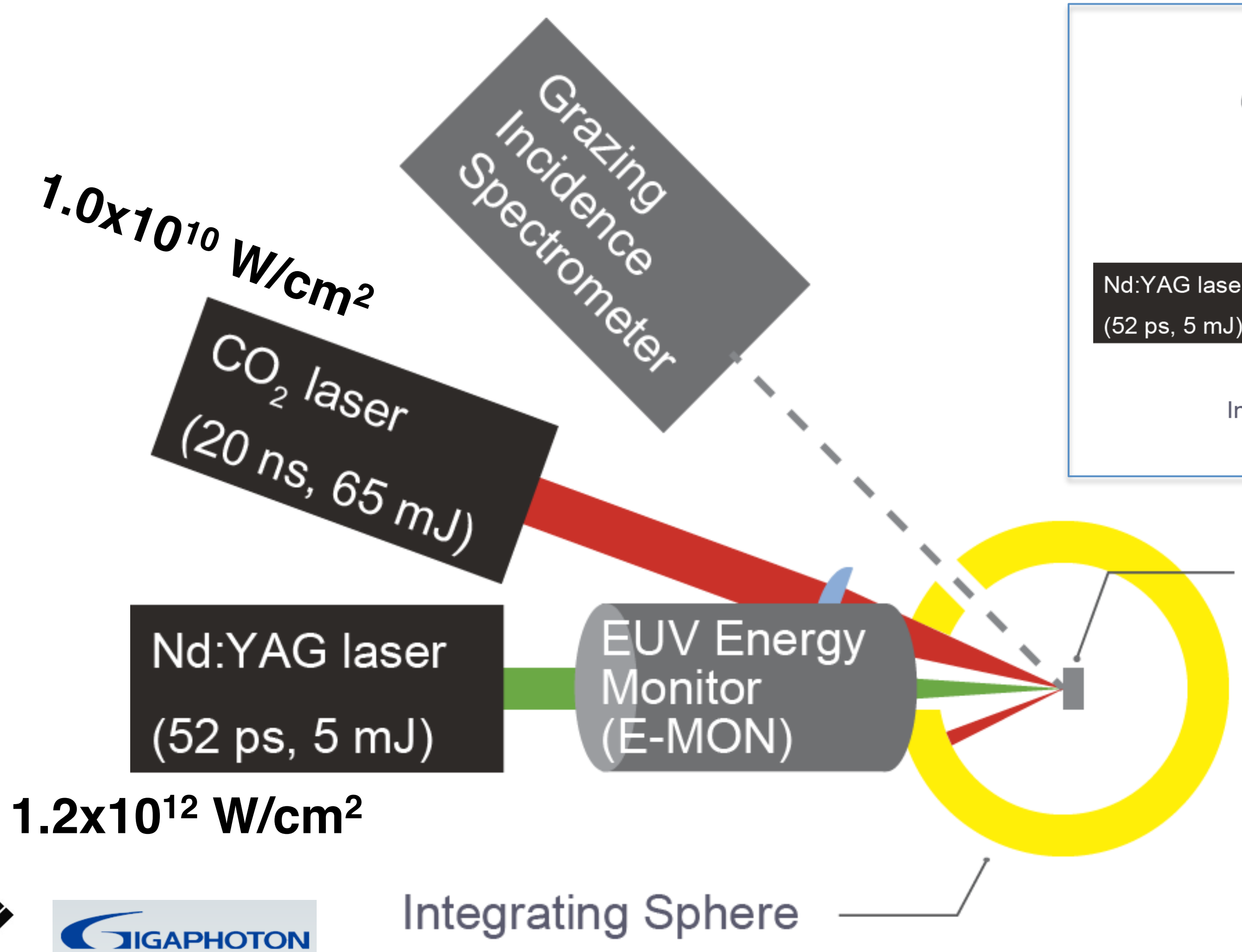
ρ: diffuse reflection factor

S: surface area of integrating sphere

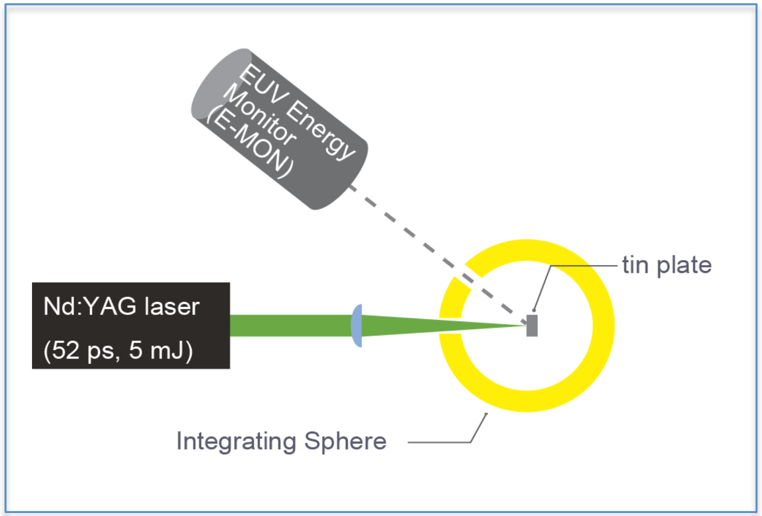
Experiment

EUV CEs and corresponding EUV spectra are measured simultaneously with η_{labs}

Top view



Side view



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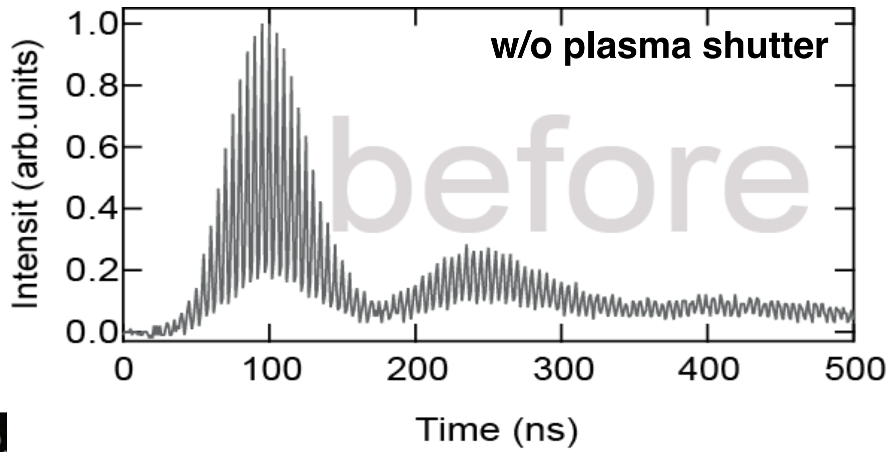
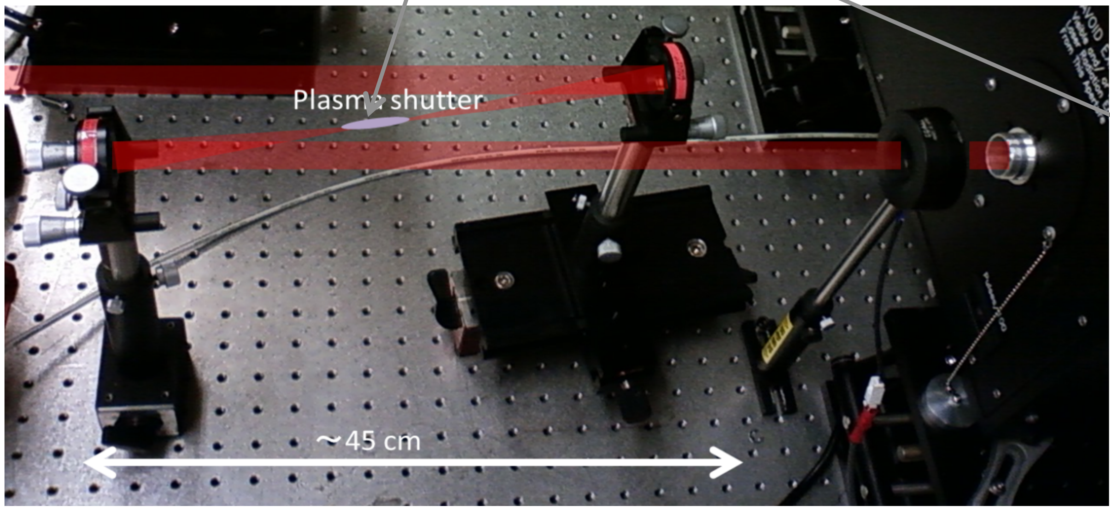
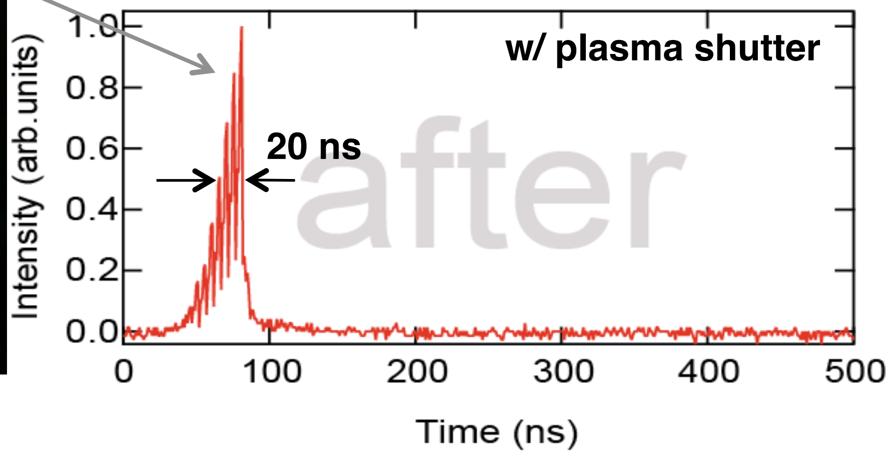
Experiment

Plasma Shutter shortens pulse width of CO_2 laser used in the experiment



Air breakdown





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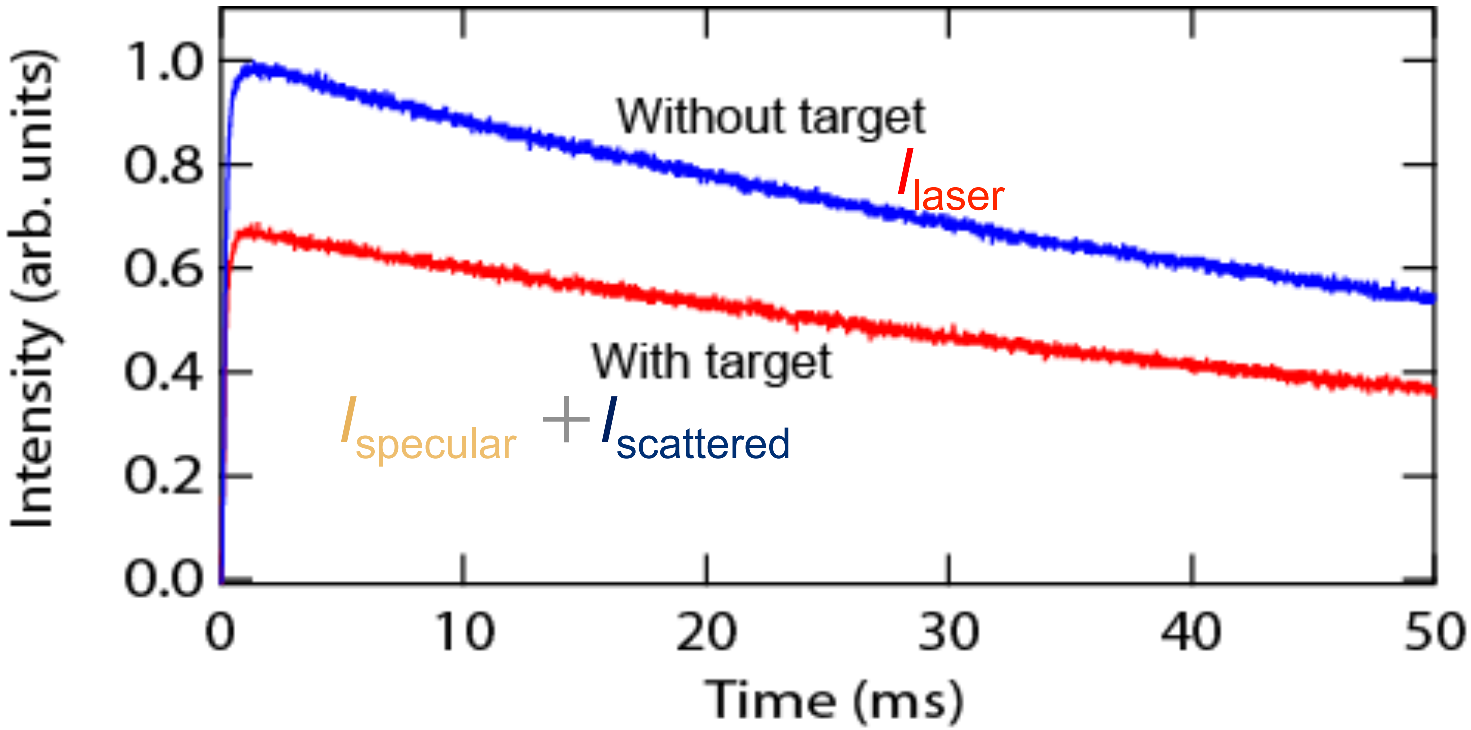
Experiment

Reduced signal from the detector indicates absorption of CO_2 laser by plasma



$$\eta_{laser\ abs.} = 1 - \frac{I_{specular} + I_{scatter}}{I_{laser}}$$

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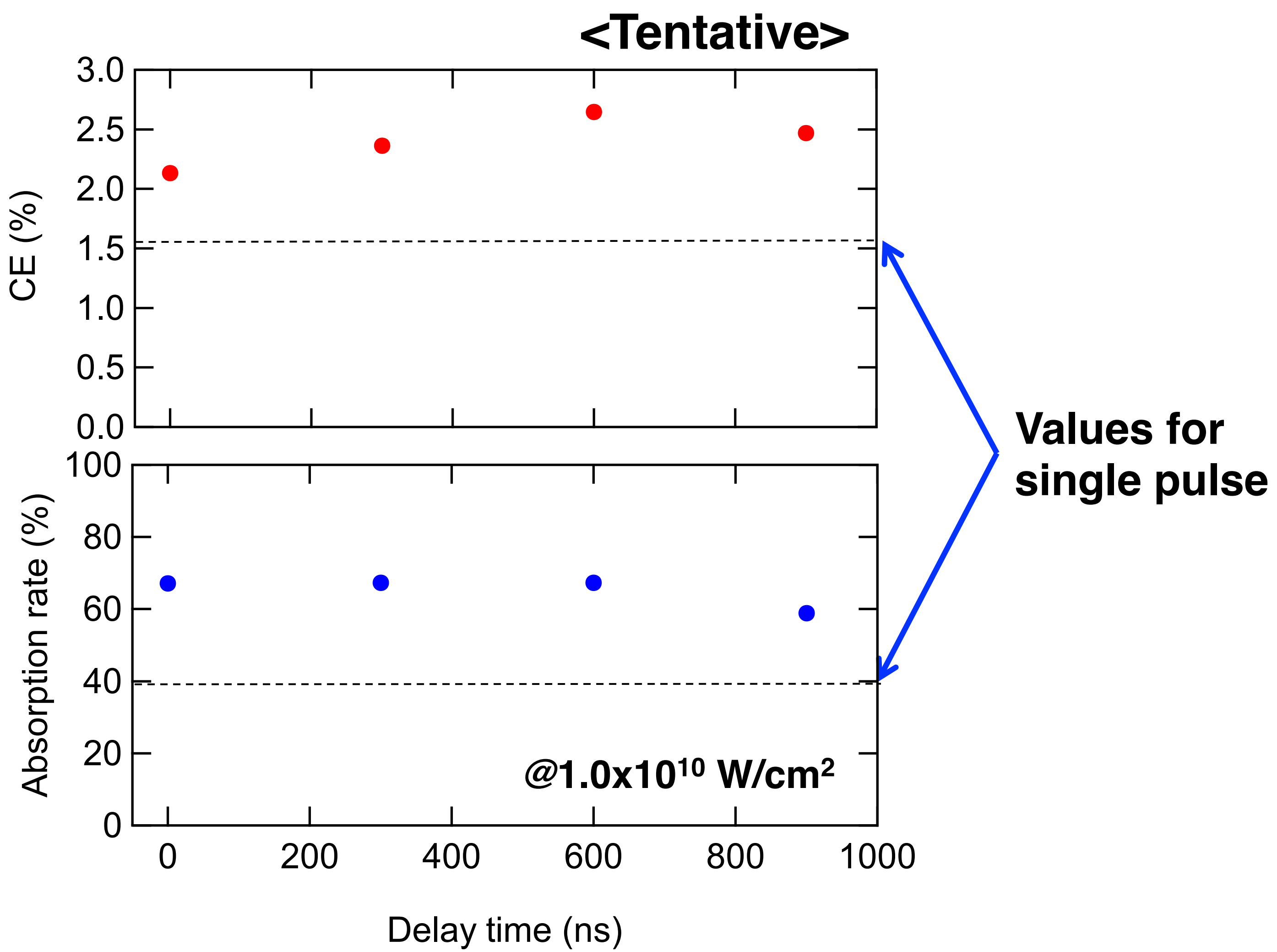
Experiment

Increase in CE and η_{labs} show clear correlation between them, validating theoretical predictions



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Summary

☑ To improve EUV CE, increase of laser absorption rate is effective.

☑ For validation, we have developed an integrating photo-sphere dedicated for CO_2 laser absorption measurement.

☑ We measured EUV CE at 13.5 nm and the drive laser absorption rate for single- and double-pulse cases, and found tight correlation between them.

Acknowledgements

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